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UNITED STATES
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HAROLD L. ICKES, SECRETARY

BUREAU OF MINES
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INFORMATION CIRCULAR

SULFUR IN THE PRODUCTS OF COMBUSTION OF FUELS

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BY

L. R. BURDICK AND J. F. BARKLEY

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UNITED STATES DEPARTMENT OF THE INTERIOR - BUREAU OF MINES

SULFUR IN THE PRODUCTS OF COMBUSTION OF FUELS[1]

By L. R. Burdick[2] and J. F. Barkley[3]

When fuels containing sulfur are burned much of the sulfur usually goes into the gaseous products of combustion as sulfur dioxide (SO_2). Some sulfur trioxide (SO_3) is also produced. In the case of coal (1)[4] or coke, part of the sulfur will be found in the refuse and in the solids carried with the gases. Sulfur unites readily with oxygen and moisture to form corrosive acids and is therefore a potential source of destruction. For example, 1 ton of coal analyzing 2-1/2 percent sulfur would contain 50 pounds. Assuming that, upon burning, 90 percent would form as sulfur dioxide in the gases, 45 pounds could and probably does eventually form about 138 pounds or more than 9 gallons of concentrated sulfuric acid or its equivalent in diluted form. Sulfur in the air of cities is considered the source of much damage. Since it usually comes chiefly from the burning of fuels, questions have arisen as to the resulting distribution of sulfur in fuels when burned; as to the part that remains in the refuse; the part that lodges in the fuel-burning equipment; and the part that goes into the atmosphere.

This paper is a review of published information on these questions.

REVIEW OF INVESTIGATIONS

Field Work

Benner

Benner (2) gives the distribution of the sulfur as noted by Bailey. He reports 53.0 to 55.0 percent passing out as sulfur gases, 39.6 to 42.3 percent absorbed in soot and mainly escaping, and 4.8 to 5.4 percent left behind in the cinder. He also has reported the percentage of sulfur found in soot from various sources:

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[1] The Bureau of Mines will welcome reprinting of this paper, provided the following footnote acknowledgment is used: "Reprinted from Bureau of Mines Information Circular 7065."

[2] L. R. Burdick, associate engineer, Fuel Economy Service, Bureau of Mines.

[3] J. F. Barkley, supervising engineer, Fuel Economy Service, Bureau of Mines.

[4] Figures in parentheses refer to items in the bibliography at the end of this paper.

	Sulfur, percent
35 feet from base of dining-room chimney ..	2.45
At top of boiler chimney	2.84
Kitchen chimney	3.30
Dining-room chimney	3.46
Locomotive	1.44
Do.	3.44
Locomotive crane	1.68
Do.	3.54

Browning

Browning (3) has reported data from tests of domestic boilers burning coke and anthracite fuels. A part of the solid material emitted from the chimneys was collected and analyzed. With both fuels the sulfur content, expressed as SO_3, was 5 percent.

Cohen and Ruston

Cohen and Ruston (4) have reported the resulting sulfur distribution found by Cohen and Hefford from coals burning on a domestic grate as follo

	Coal A, percent	Coal B, percent
As sulfur gases	71.8	60.0
In soot and escaping	14.5	11.9
Left in cinder	13.7	28.1

They also present figures for the sulfur content of soot:

	Sulfur, percent
Soot from fire-grate chimney .	3.0
Soot from boiler chimney	2.7
Soot from dining room	2.5
Soot from kitchen	2.2
Soot from study	2.3
Soot from kitchen	1.5

Leclerc

Leclerc (5) obtained data on the sulfur and ash content of the refu taken from the grates of domestic heating units and a kitchen stove burn coals of known analysis at various combustion rates. He assumed that al of the solid material from the combustion process contained the same rat of sulfur to ash as the grate refuse, calculated the percentage of the s fur of the coal in all solid material, and called the remainder the perc age of the sulfur of the coal going out as gas in the flue gases. His figures for the above values are given in tables 1 and 2. He noted that slightly more sulfur was held in the ash at the lower combustion rates.

TABLE 1. - Sulfur in solid material and flue gases from domestic heating unit
(Tests with coal of 7.5 percent volatile
matter, 3.5 percent ash, 0.83 percent sulfur)

rning equipment	Combustion rate, kg. per hr.	Analysis of grate refuse		Sulfur distribution, expressed as percent of sulfur of coal	
		Ash, percent	Sulfur, percent	To solid material	To flue gases
azine-feed estic furnace	1.225	30.5	0.85	11.6	88.4
Do.	1.315	49.1	.73	6.3	93.7

TABLE 2. - Sulfur in solid material and flue gases from domestic heating unit and kitchen stove
(Tests with coal of 13.25 percent volatile
matter, 2.22 percent ash, 0.98 percent sulfur)

ning equipment	Combustion rate, kg. per hr.	Analysis of grate refuse		Sulfur distribution, expressed as percent of sulfur of coal	
		Ash, percent	Sulfur, percent	To solid material	To flue gases
-fired do- ic furnace	0.823	18.9	0.88	10.5	89.5
Do.	1.000	39.2	.92	5.36	94.64
Do.	2.170	51.05	.89	3.92	96.08
hen stove	1.050	66.90	.84	2.90	97.1
Do.	2.900	64.85	.60	2.10	97.9

olls

P. Nicholls, Bureau of Mines, Pittsburgh, Pa., reports the sulfur distribution
coal burned on a 60-square-foot chain-grate stoker at a rate of 13 pounds per
re foot of grate surface per hour. The sulfur found in the ash from a 6-hour
amounted to 3.1 percent of the sulfur in the coal; that determined volumet-
lly from the gases leaving the furnace was 93.5 percent, making a total of
percent of the sulfur of the coal accounted for in the ash and flue gases.

ce

Pearce (6) directed experiments with lime added to coal before firing under
ler and observed the effect on the sulfur content of the ash and exit gases.
was added to the coal as limewater (water saturated with lime), lime slurry,
halk slurry and was fed onto the coal in the hoppers at rates of about 30 to
llons of limewater per ton of coal, 20 and 40 pounds of lime as slurry per ton
al, and 40 pounds of chalk per ton of coal. He concluded that addition of
compounds did not reduce the sulfur going to the escaping gases enough to
practical importance, but that different results might be obtained in a
rized-fuel furnace. Some of the data presented are given in table 3.

He also has given the information shown in table 4 on the amount of the coal sul fur accounted for in the flue gases and grate ash from a power station in Great Britain and suggests that some of the unaccounted for sulfur may have been in the fly-ash, or in the gas other than as SO_2 or SO_3.

Ardern and Wheeler

Ardern and Wheeler (7), in reporting the work of the London Power Co. on washers for removing sulfur from flue gases, have given the sulfur distributio shown below:

Coal per hour .... pounds	8,630	4,690	4,330
Sulfur in coal .... percent	0.90	0.89	0.84
Sulfur in coal per hour .... pounds	77.6	41.7	36.4
Sulfur in flue gases per hour . do	73.0	36.0	38.8
Sulfur in ash per hour ..... do	2.15	.7	.7

Johnstone

Johnstone (8) analyzed for sulfur compounds in the flue gases from plants fired by chain-grate stokers and pulverized fuel. The results of this work are shown in tables 5 to 8. He also made analyses of fly-ash accumulations in soot hoppers and corners of construction at stoker-fired and pulverized-fuel plants. The sulfur present in these accumulations was as given in table 9.

Victoir

Victoir (9) has presented figures for the sulfur distribution from a lo volatile coal with a sulfur content of 0.83 percent, burned in pulverized fo under a 1238-hp. boiler. Under the conditions of the test 0.8 percent of the sulfur of the coal remained in the ash-pit refuse, 0.5 percent in the soot hoppers, and 98.6 percent left the boiler in the flue gases either in the fl ash or as gaseous compounds. The data indicated that the gaseous sulfur woul account for approximately 98 percent of the sulfur of the coal.

Sherman

Sherman (10) analyzed furnace-gas samples for sulfur content. These we taken a few inches from the side wall of the furnaces of power boilers. He not find any relation between the amount of SO_2 in the gases and the rate of firing. He also analyzed for the sulfur content of slags, pit ash, and fly- from the same plants. The results of this work are summarized in table 10.

Federal Central Heating Plant, Washington, D. C.

Test data taken when burning Pennsylvania medium-volatile coal on larg underfeed stokers are presented in table 11. The percentage of the sulfur the coal that left the equipment as gas is shown by difference to be abou 98 percent.

TABLE 3. - Sulfur in ashes and flue gases

(Experiments with the addition of lime or chalk to coal)

Sulfur in dry coal, percent	Percent of sulfur of coal found in ashes	Percent of sulfur of coal found in gas
	No lime or chalk added	
1.51	3	89
1.71	1	76
3.45	1	78
1.17	3	85
1.05	3	83
0.89	2	92
1.77	1	92
1.01	3	100
1.00	2	100
0.85	2	92
	20 lb. lime added per ton of coal	
2.15	3	84
1.59	3	99
2.43	7	86
	40 lb. lime added per ton of coal	
1.40	4	99
1.12	3	100
1.30	4	67
	40 lb. chalk added per ton of coal	
1.03	3	89
1.96	2	73
1.32	2	74
1.00	3	39

46

TABLE 4. - Sulfur accounted for in the flue gases and the ash remaining on the grate

Experiment No.		Sulfur in coal, percent	Percent of sulfur of coal in grate ash and flue gases
II	a	0.81	72
	b	.81	73
	c	.82	74
	d	.82	72
	e	.74	97
	f	.74	88
	g	.73	93
	h	.73	92
III	a	.91	57
	b	.91	65
	c	1.01	85
	d	1.01	85
	e	.76	90
IV	a	.89	68
	b	.89	73
	c	.95	67
V	a	1.26	63
	b	1.26	60
	c	.71	103
	d	.71	97
VI	a	.86	77
	b	.86	78
	c	.93	78
	d	.93	83
VII	a	.85	81
	b	.85	87
	c	.90	77
	d	.90	68
VIII	a	.75	88
	b	.75	93
IX	a	.81	73
	b	.81	70
	c	.79	70
	d	.79	72
X	a	.82	87
	b	.82	120
XI	a	1.10	108
	b	1.10	65
XII	a	.91	92
	b	.91	70
	c	.81	80
	d	.81	70
	e	.78	74
	f	.78	74
	g	.90	61
XIII	a	.78	74
	b	.78	70
	c	.71	66
	d	.73	66

TABLE 5. - Sulfur in flue gases from chain-grate stoker burning Illinois coal from Christian County1/

(Coal composition: Carbon, 55.6 percent; sulfur, 4.45 percent)

Point of sampling	SO_2 by volume, percent	SO_3 by volume, percent	Percent of sulfur of coal in flue gases
1st pass of boiler ..	0.291	0.0076	90
2d pass of boiler ...	.289	.0117	93
Economizer outlet ...	.275	.0054	91
Induced-fan inlet ...	.100	.0019	79

1/ Averaged from various boiler ratings.

TABLE 6. - Sulfur in flue gases from chain-grate stoker burning Ohio coal1/

(Coal composition: Carbon, 67.7 percent; sulfur, 3.13 percent)

Point of sampling	SO_2 by volume, percent	SO_3 by volume, percent	Percent of sulfur of coal in flue gases
Economizer inlet	0.108	0.0032	55
Economizer outlet ...	.0914	.0025	47

1/ Averaged from various boiler ratings.

TABLE 7. - Sulfur in flue gases from chain-grate stoker burning Illinois coal from Williamson County1/

(Coal composition: Carbon, 63.9 percent; sulfur, 2.1 percent)

Point of sampling	SO_2 by volume, percent	SO_3 by volume, percent	Percent of sulfur of coal in flue gases
In superheater loop .	0.124	0.0028	78
2d pass of boiler ...	.171	.0005	99
Economizer outlet ...	.068	.0014	57

1/ Averaged from various boiler ratings.

Original from THE OHIO STATE UNIVERSITY

TABLE 8. - Sulfur in flue gases from pulverized-fuel boiler burning Illinois coal[1]

(Coal composition: Carbon, 58.2 percent; sulfur, 4.67 percent)

Point of sampling	SO_2 by volume, percent	SO_3 by volume, percent	Percent of sulfur of coal in flue gases
1st pass of boiler ..	0.419	0.0035	97
Economizer outlet ..,	.414	.0029	109
Induced-fan inlet ...	.385	.0029	109

[1] Averaged from various boiler ratings.

TABLE 9. - Sulfur in fly ash from soot hoppers and corners of construction

Type of firing	Type of coal	Sulfur in coal (as rec'd.) percent	Source of sample	Sulfur, presse percent
Chain-grate stoker	Illinois.....	4.45	Economizer outlet..........	15.
...... Do.........	.. do........	4.45	Top tubes of economizer	17.
...... Do.........	Ohio.........	3.18	Economizer inlet...........	
...... Do.........	.. do........	3.18	Economizer outlet	
Underfeed stoker..	Pennsylvania.	3.33	Economizer.................	
Chain-grate stoker	Ohio.........	3.4	....do.....................	
...... Do.........	Illinois.....	2.1	Economizer outlet..........	
...... Do.........	.. do........	2.1	2d pass of boiler..........	
Pulverized coal...	.. do........	4.67	Economizer settling chamber.	
...... Do.........	.. do........	4.67	Induced-fan inlet..........	
...... Do.........	West Va.-Ky..	1.07	Economizer.................	
...... Do.........	West Virginia	.58	...do......................	
Chain-grate stoker	.. do........	.80	Economizer outlet..........	

Burning equipment	Traveling-grate stoker	Underfeed stoker		Traveling-grate stoker	Powdered-coal burners	Powdered-coal burners	Traveling-grate stoker	Mechanical atomizer burners
Kind of fuel	Pittsburgh No. 8	Pittsburgh No. 8		Illinois	Illinois	Illinois	Anthracite	Fuel oil
Fuel composition, percent:								
Carbon..........................	72.4	77.1	72.5	67.8	67.9	65.5	72.6	85.3
Sulfur..........................	3.6	1.1	3.1	4.4	1.6	3.8	1.2	1.8
Fraction of sulfur of fuel in gas near furnace sidewall....percent								
Average.........................	44	43	51	34	42	66	65	71
Maximum.........................	90	79	93	85	100	100	88	95
Sulfur content expressed as percent SO_3:								
In coal ash.....................	1.5	1.2	1.3	4.0	3.0	15.3	2.3	
In slag from sampling tube in furnace......................	8.9			6.4				
In slag from boiler tubes.....	.2						2.1	
In slag from boiler tubes, next to tube................				6.6				
In slag from boiler tubes, outside of pieces..............			.2	.2				
In slag from lower water-tube slag screen.................					.3	1.2		
In slag from tubes of rear water wall..................					.5	.6		
In slag from furnace gas......	1.9	.5	.4				4.3	
In ash from ash pit..........	.4	.1	.6				2.8	
In dust from third pass.......							2.2	
In slag from front wall.......		.0						
In slag from bridge wall......		.1						
In slag, white pieces from lower side wall............		.1						
In dust from soot chamber.....		1.5	1.1					
In dust from furnace gas......					4.4	12.8		
In dust from uptake...........					.5	3.8		

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TABLE 11. - Sulfur in products of combustion from Pennsylvania medium-volatile bituminous coal burned on multiple-retort underfeed stoker

Test No.	1	2	3	4	Ave.	5	6	Ave.
Coal per sq. ft. of grate per hr............ lb.	23.0	23.0	22.9	23.2	23.0	40.4	40.6	40.5
Sulfur in coal..........................percent	1.36	.97	1.17	1.21	1.18	1.40	1.64	1.52
Sulfur in ash to pit......................do...	.2	.2	.1	.1	.2	.1	.1	.1
Sulfur in stoker siftings.................do...	1.5	1.6	1.7	1.7	1.6	2.2	2.6	2.4
Sulfur in fly-ash from precipitator........do...	2.3	2.4	2.3	2.3	2.3	.9	.8	.9
Sulfur in fly-ash from cinder trap.........do...	.4	.3	.3	.4	.4	.5	.6	.6
Sulfur in pit ash......percent of sulfur of coal	1.2	1.2	.7	.8	1.0	.5	-	.5
Sulfur in stoker siftings.................do...	.4	.7	.6	.5	.6	.4	.5	.5
Sulfur in fly-ash caught by precipitator....do...	.6	.7	.8	.7	.7	1.2	.7	1.0
Sulfur in fly-ash caught by cinder trap.....do...	.1	.1	.1	.1	.1	.5	.3	.4
Sulfur in fly-ash going to atmosphere (Est.)do...	.1	.1	.1	.1	.1	.1	.1	.1
Sulfur accounted for by solid material......do...	2.4	2.8	2.3	2.3	2.5	2.7	-	2.5
Sulfur to flue gases (by dif.)..............do...	97.6	97.2	97.7	97.7	97.5	97.3	-	97.5

Chicago Association of Commerce

Tables 12 and 13 contain data from investigations by the Chicago Association of Commerce (11). This work included observations of the sulfur content of solids and gases discharged from locomotive smokestacks, and of the ash and clinker passed through the grate.

Nicholls and Reid

Nicholls and Reid (12) (13) analyzed the coal and the resulting fly-ash, furnace ash, and tapped slag from many pulverized-fuel plants using dry-bottom and slag-tap furnaces. The sulfur content was found to be as shown in tables 14 and 15.

Leclerc

Leclerc (14) also analyzed the coal, pit ash, and fly-ash at a pulverized-coal installation, taking simultaneous samples of the fly-ash at various points in the path of the flue gases. His results are shown in table 16.

Pier and Crowder

Pier and Crowder (15) have published the analysis of flue dust from a pulverized-fuel-burning installation. The SO_4 content was 3.1 percent.

Laboratory Experiments

Foerster and Landgraf

Foerster and Landgraf (16) experimented with $CaSiO_3$, kaolin, and $CaCO_3$ when burned in air with FeS_2 at 900°. They concluded that the amount of sulfur absorbed was least with kaolin and most with $CaCO_3$. They also did some laboratory work on the retention of sulfur by the ash in the burning of coals and low-temperature cokes of high ash content and concluded that more sulfur was retained when the fuel was burned in a crucible than when burned in a thin layer at 900° in a current of air.

TABLE 12. - Sulfur in fly ash and flue gases from a locomotive

Test No.	Source of coal	Miles per hour	Brick arch in fire-box	Sulfur in coal fired, percent	Sulfur in fly ash			Sulfur in flue gases, percent of sulfur of coal
					Percent of fuel fired	Percent of fly ash	Percent of sulfur of coal	
2715	Macoupin Co. (Ill.)	7.33	No	4.05	0.059	2.54	1.5	-
2716		14.66	No	4.05	.058	2.30	1.4	-
2717		14.66	No	4.05	.139	2.71	3.4	-
2718		18.33	No	4.05	.184	2.74	4.5	-
2719[1]		14.66	No	4.05	.071	2.76	1.8	-
2720		7.33	Yes	4.05	.085	3.38	2.1	-
2721		14.66	Yes	4.05	.080	2.79	2.0	-
2722		14.66	Yes	4.05	.044	1.05	1.1	19.55
2723		18.33	Yes	4.05	.225	2.95	5.6	11.92
2724		22.00	Yes					
2796	Marion Co. (Ill.)	7.33	Yes	2.82	.087	2.92	3.1	23.58
2797		14.66	Yes	2.82	.086	2.26	3.1	27.91
2798		14.66	Yes	2.82	.235	3.76	8.3	-
2799		14.66	Yes	2.82	.104	4.06	3.7	23.65
2700[1]		14.66	Yes	2.82	.057	2.11	2.0	6.52
2790	Saline Co. (Ill.)	7.33	Yes	2.33	.060	2.39	2.6	1.20
2791		14.66	Yes	2.33	.027	1.45	1.2	14.46
2792		14.66	Yes	2.33	.065	1.42	2.8	46.40
2793		18.33	Yes	2.33	.113	1.60	4.9	56.91
2794		22.00	Yes					
2795[1]		14.66	Yes	2.33	.068	1.65	2.9	20.00
2732	Sangamon Co. (Ill.)	7.33	Yes	3.56	.083	2.69	2.3	72.42
2733		14.66	Yes	3.56	.057	2.94	1.6	33.7
2734		14.66	Yes	3.56	.096	3.02	2.7	61.8
2735		18.33	Yes	3.56	.049	.76	1.4	9.6
2736		22.00	Yes					
2737[1]		14.66	Yes	3.56	.134	3.58	3.8	47.1
2748	Vermillion Co. (Ill.)	7.33	Yes	2.69	.121	4.95	4.5	-
2749		14.66	Yes	2.69	.053	1.85	2.0	18.
2750		14.66	Yes	2.69	.081	2.07	3.0	16.
2751		18.33	Yes	2.69	.138	1.54	5.1	15.
2752		22.00	Yes					
2753[1]		14.66	Yes	2.69	.037	1.63	1.4	18.
2725	Williamson Co. (Ill.)	7.33	No	.70	.093	2.98	13.3	-
2726		14.66	No	.70	.046	2.12	6.6	-
2727		14.66	No	.70	.068	.97	9.7	5.
2728		18.33	No	.70	.281	2.63	40.1	10
2729		22.00	No					
2730[1]		14.66	No	.70	.068	2.01	9.7	8
2738		7.33	Yes	.70	.066	2.35	9.4	33
2739		14.66	Yes	.70	.044	1.62	6.3	47
2740		14.66	Yes	.70	.030	1.55	4.3	1
2741		18.33	Yes	.70	.020	.85	2.9	-
2742[1]		14.66	Yes	.70	.070	1.69	10.0	

[1] Fired by an inexperienced fireman.

TABLE 12. - Sulfur in fly ash and flue gases from a locomotive (Continued)

Test No.	Source of coal	Miles per hour	Brick arch in fire-box	Sulfur in coal fired, percent	Sulfur in fly ash			Sulfur in flue gases, percent of sulfur of coal
					Percent of fuel fired	Percent of fly ash	Percent of sulfur of coal	
3	Greene Co. (Ind.)	7.33	Yes	2.72	0.066	2.55	2.4	57.17
4		14.66	Yes	2.72	.152	1.93	5.6	23.68
5		14.66	Yes	2.72	.124	1.92	4.6	21.58
6		18.33	Yes	2.72	.175	1.72	6.4	73.20
7 1/		14.66	Yes	2.72	.064	1.18	2.4	-
0	Sullivan Co. (Ind)	7.33	Yes	3.25	.096	3.08	3.0	-
1		14.66	Yes	3.25	.065	2.48	2.0	44.80
2		14.66	Yes	3.25	.104	2.46	3.2	39.47
3		18.33	Yes	3.25	.149	2.02	4.6	55.41
4		22.00	Yes					
5 1/		14.66	Yes	3.25	.068	2.51	2.1	28.62
6		7.33	No	3.25	.091	2.70	2.8	44.27
7		14.66	No	3.25	.066	2.62	2.0	17.20
8		14.66	No	3.25	.121	2.46	3.7	9.23
		18.33	No	3.25	.266	2.05	8.2	16.95
	Vermillion Co. (Ind.)	7.33	Yes	4.28	.260	3.74	6.1	47.41
		14.66	Yes	4.28	.104	3.38	2.4	85.37
		14.66	Yes	4.28	.123	2.58	2.9	36.00
		18.33	Yes	4.28	.203	2.03	4.7	37.10
		22.00	Yes					
1/		14.66	Yes	4.28	.152	2.84	3.6	41.54
		7.33	No	4.28	.030	1.73	.7	64.44
		14.66	No	4.28	.091	2.58	2.1	50.37
		14.66	No	4.28	.185	2.62	4.3	10.28
		18.33	No	4.28	.303	2.36	7.1	23.46
	Vigo Co. (Ind.)	7.33	Yes	4.75	.077	3.76	1.6	45.26
		14.66	Yes	4.75	.118	2.82	2.5	14.32
		14.66	Yes	4.75	.168	3.72	3.5	54.93
		18.33	Yes	4.75	.179	2.94	3.8	78.44
		22.00	Yes					
/		14.66	Yes	4.75	.189	3.34	4.0	92.63

red by an inexperienced fireman.

TABLE 13. - Sulfur in ash and clinker from a locomotive grate

Source of coal	Sulfur in ash and clinker, percent	Weight of ash and clinker in percent of coal fired	Sulfur in ash and clinker, percent of sulfur of coal
With brick arch			
Marion Co. (Ill.)......	2.83	19.98	20.1
Saline Co. (Ill.)......	1.55	8.64	5.8
Sangamon Co. (Ill.)....	1.85	12.40	6.4
Vermillion Co. (Ill.)..	1.65	15.02	9.2
Williamson Co. (Ill.)..	.48	11.58	8.0
Greene Co. (Ind.)......	1.73	14.26	9.1
Sullivan Co. (Ind.)....	2.35	15.03	10.9
Vermillion Co. (Ind.)..	3.17	19.06	14.1
Vigo Co. (Ind.)........	1.72	15.49	5.6
Average	1.92	14.61	9.9
Without brick arch			
Macoupin Co. (Ill.)....	3.91	10.84	10.5
Williamson Co. (Ill.)..	.52	12.29	9.1
Sullivan Co. (Ind.)....	2.24	13.89	9.6
Vermillion Co. (Ind.)..	3.30	18.73	14.4
Average	2.49	13.94	10.9

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Coal				Heat release, B.t.u. per sq. ft. of horizontal area per hour	Combustible in fly ash, percent	Sulfur, expressed as percent SO_3	
Source	Rank	Percent ash	Percent sulfur			Slag - as received	Fly ash, combustible-free[1]
Kansas.....	Bituminous	12.4	4.1	389,000	-	2.4	-
Illinois...	do	11.7	4.1	714,000	1.5	.7	3.2
Penna......	Semi-bit.	8.3	3.4	-	-	.1	-
Illinois...	Bituminous	-	-	-	-	.2	-
Oklahoma...	do	11.7	2.3	430,000	4.4	.3	1.9
-	Petroleum coke	1.0	-	740,000	5.6	.1	25.3
Ohio.......	Bituminous	10.3	3.5	494,000	5.6	.3	1.9
Colorado...	Lignite	5.9	.6	540,000	2.1	.3	2.3
Ohio.......	Bituminous	12.1	2.6	605,000	-	.1	-
Penna......	do	11.3	1.9	750,000	12.0	.0	1.2
-	do	-	-	-	-	.2	-
Kentucky...	do	6.4	.5	545,000	27.6	.1	1.4
West Va.	Semibit.	-	-	-	-	.0	-
Do	do	6.1	.6	757,000	13.9	.3	2.4
Do	do	6.0	.6	825,000	6.3	.4	2.4
Do	do	6.5	.6	905,000	27.1	.2	1.4
Penna.	Bituminous	12.15	1.15	769,000	-	.3	-
-	Semibit.	5.2	.6	604,000	41.1	.1	1.5 (from deposits)
-	do	-	-	-	-	.3	-
-	do	-	-	-	-	.3	-

[1] Sampled from gas stream, except as noted.

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TABLE 15. - Sulfur content of furnace ash from dry-bottom plants

Coal	Sulfur in furnace ash, expressed as percent SO_3
-	0.3
-	.2
Semibituminous...	.6

TABLE 16. - Results of analyses of dusts sampled in the circuit of the flue gases from pulverized coal

No. of sample	Nature of sample; place of sampling	Total sulfur, percent	Ash, per-cent
1	Coal -......................	1.35	22.2
2	Ash (ash pit)..............	.30	95.5
3	Outlet of the furnace......	.47	59.4
4	Reheater - 1st hopper......	.55	59.8
5	Reheater - 2d hopper.......	.47	59.0
6	Economizer - 1st hopper....	.49	64.3
7	Economizer - 2d hopper.....	.41	49.9
8	Inlet of dust remover	.37	78.1
9	Outlet of dust remover.....	.70	78.5

Trifonov and Trifonov

Trifonov and Trifonov (17) obtained data on the behavior of the individual sulfur compounds in coal and coke during combustion by experiments in the laboratory with a Bulgarian coal and coke whose ash content had been reduced by a flotation process and practically all sulfur except the organic removed by extraction with cold dilute HNO_3. They mixed known amounts of inorganic sulfur compounds, ash constituents, and other compounds with this purified coal or coke, burned 4 grams of the mixture at 900° C. in an electrically heated muffle, and analyzed the ash residue for sulfur content. Their conclusions, based on the data thus obtained (presented in tables 17, 18, 19, 20) were that:

1. There is no noteworthy difference in the process of sulfur distribution between coal and coke.
2. All inorganic sulfur compounds in coal or coke are more or less unstable and lose some of their sulfur at a temperature not exceeding 900° C., the loss with the various compounds ranging from the entire amount with FeS_2 to a small part with $CaSO_4$.
3. There is no noteworthy effect of ash on the behavior of any inorganic sulfur compound except FeS_2. $CaCO_3$, however, has strong sulfur binding power, and holds in the ash residue a part of the sulfur evolved from the unstable compounds.
4. Sulfur from organic compounds or FeS_2 is partly caught in the ash by an ash composed of basic silicates and $CaCO_3$, mostly due to the $CaCO_3$ and almost exclusively due to $CaCO_3$ at higher temperatures.
5. In general, for a given quantity of organic or pyritic sulfur in the fuel, the greater the basicity or the carbonate content of the ash, the more sulfur is held in the ash. The higher the ratio of "sulfur binder" to sulfur, the greater is the proportion of the organic or pyritic sulfur held in the ash, and with favorable values of this ratio, nearly all of the sulfur from organic compounds and FeS_2 remains in the ash residue.
6. Inert ash constituents, such as alumina, aluminum silicate, etc., have no effect on the sulfur distribution at temperatures up to 900° C.
7. Magnesium compounds, (carbonate, silicate) combine with evolving SO_2 but release most of it again between 800 and 900° C., and at 1,000° C., in the absence of calcium, a MgO or Mg_2SiO_4 ash retains almost no sulfur.

TABLE 17. - Coal with 1.1 percent organic sulfur, inorganic sulfur - trace, 10 parts of compound mixed with 100 parts of purified fuel

No.	Compound mixed with purified fuel	Parts of added sulfur in 100 parts of mixture	Parts of sulfur left in ash residue from combustion of 100 parts mixture at 900° C.	Added sulfur which did not remain in ash residue, percent of added sulfur
1	$CaSO_4 - 2H_2O$	1.64	1.46	10.97
2	$MgSO_4$	2.10	.06	97.15
3	CaS	3.61	2.62	27.42
4	MgS	3.23	.51	84.21
5	FeS_2	4.65	.02	99.57
				Recombined sulfur, in percent of organic sulfur.
6	$CaSiO_3$	-	.14	14
7	$MgSiO_3$	-	.02	2
8	Ca_2SiO_4	-	.21	21
9	Mg_2SiO_4	-	.02	2
10	$CaCO_3$	-	.83	83
11	$MgCO_3$	-	.07	7
12	Dolomite	-	.74	74
13	CaO	-	.94	94
14	MgO	-	.09	9
15	SiO_2	-	Trace	0
16	Al_2O_3	-	do	0
17	Kaolin	-	do	0
18	Mixture of 50 percent $CaCO_3$ and 50 percent $CaSiO_3$	-	.48	48
19	Mixture of 50 percent $MgCO_3$ and 50 percent $MgSiO_3$	-	.06	6

TABLE 18. - Coke with 0.95 percent organic sulfur, inorganic sulfur - trace, 10 parts of compound mixed with 100 parts of purified fuel

Compound mixed with purified fuel	Parts of added sulfur in 100 parts of mixture	Parts of sulfur left in ash residue from combustion of 100 parts mixture at 900° C.	Added sulfur which did not remain in ash residue, percent of added sulfur
$CaSO_4 - 2H_2O$	1.64	1.45	11.59
$MgSO_4$	2.10	.05	97.62
CaS	3.61	2.62	27.42
MgS	3.23	.49	84.83
FeS_2	4.65	.02	99.57
			Recombined sulfur, in percent of organic sulfur.
$CaSiO_3$	-	.13	15
$MgSiO_3$	-	.02	2.3
Ca_2SiO_4	-	.19	22.1
Mg_2SiO_4	-	.02	2.3
$CaCO_3$	-	.76	88.37
$MgCO_3$	-	.06	7
CaO	-	.34	97.67
MgO	-	.08	9.3
SiO_2	-	Trace	0
Mixture of 50 percent $CaCO_3$ and 50 percent $CaSiO_3$	-	.44	51.62
Mixture of 50 percent $MgCO_3$ and 50 percent $MgSiO_3$	-	.05	5.81

TABLE 19. - Coal with 1.1 percent organic sulfur, inorganic sulfur - trace, 15 parts of compounds mixed with 100 parts purified fuel

No.	Compounds mixed with purified fuel	Parts of added sulfur in 100 parts of mixture	Parts of sulfur left in ash residue from combustion of 100 parts mixture at 900° C.	Calculated value for parts of sulfur in the ash residue per 100 parts original mixture based on a summation of the effects of both compounds as given in table 17[1]
1	$CaSO_4$, $2H_2O$ (5 parts), $CaSiO_3$ (10 parts).....	0.78	0.77	0.82
2	$CaSO_4$, $2H_2O$, Ca_2SiO_4..	.78	.85	.89
3	CaS, $CaSiO_3$...........	1.73	1.36	1.38
4	CaS, Ca_2SiO_4..........	1.73	1.42	1.45
5	$MgSO_4$, $CaSiO_3$.........	1.00	.18	.15
6	$MgSO_4$, Ca_2SiO_4........	1.00	.26	.22
7	MgS, $CaSiO_3$...........	1.54	.38	.37
8	MgS, Ca_2SiO_4..........	1.54	.46	.44
9	FeS_2, $CaSiO_3$..........	2.23	.25	.14
10	FeS_2, Ca_2SiO_4.........	2.23	.37	.21
11	FeS_2, $MgSiO_3$..........	2.23	.04	.03
12	FeS_2, Mg_2SiO_4.........	2.23	.04	.03
13	$CaSO_4$, $2H_2O$, $MgSiO_3$................	.78	.74	.72
14	MgS, $MgSiO_3$...........	1.54	.28	.27
15	$MgSO_4$, Mg_2SiO_4........	1.00	.08	.05
16	CaS, Mg_2SiO_4..........	1.73	1.31	1.28
17	$CaSO_4$, $2H_2O$, SiO_2.....	.78	.70	.70
18	CaS, SiO_2.............	1.73	1.27	1.26
19	$CaSO_4$, $2H_2O$, $CaCO_3$....	.78	1.58	1.53
20	$MgSO_4$, $CaCO_3$..........	1.00	1.36	.86
21	$CaSO_4$, $2H_2O$, mixture of 50 percent $CaCO_3$ and 50 percent $CaSiO_3$.	.78	1.14	1.16
22	CaS, mixture of 50 percent $CaCO_3$ and 50 percent $CaSiO_3$...........	1.73	1.70	1.72
23	$MgSO_4$, mixture of 50 percent $CaCO_3$ and 50 percent $CaSiO_3$........	1.00	.60	.50
24	MgS, mixture of 50 percent $CaCO_3$ and 50 percent $CaSiO_3$..........	1.54	.70	.72

See footnote on page 21.

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TABLE 19. - Coal with 1.1 percent organic sulfur, inorganic sulfur - trace, 15 parts of compounds mixed with 100 parts purified fuel (Continued)

o.	Compounds mixed with purified fuel	Parts of added sulfur in 100 parts of mixture	Parts of sulfur left in ash residue from combustion of 100 parts mixture at 900° C.	Calculated value for parts of sulfur in the ash residue per 100 parts of original mixture based on a summation of the effects of both compounds as given in table 17[1]
5	FeS_2, mixture of 50 percent $CaCO_3$ and 50 percent $CaSiO_3$........	2.23	.93	.50
6	$CaSO_4$, $2H_2O$, mixture of 50 percent $MgCO_3$ and 50 percent $MgSiO_3$.	.78	.76	.75
7	MgS, mixture of 50 percent $MgCO_3$ and 50 percent $MgSiO_3$...........	1.54	.30	.30
	Coke with 0.95 percent organic sulfur, inorganic sulfur - trace			
	$CaSO_4$, $2H_2O$, Ca_2SiO_4..	.78	.91	.89
	CaS, Ca_2SiO_4..........	1.73	1.46	1.45
	$CaSO_4$, $2H_2O$, $MgSiO_3$...	.78	.74	.72
	MgS, $MgSiO_3$...........	1.54	.28	.27
	FeS_2, $CaCO_3$...........	2.23	1.81	.77

LE 20. - Volatilization at high temperature of the ash sulfur combined with magnesium (coke with 0.95 percent organic sulfur, inorganic sulphur - trace, 10 parts of compound mixed with 100 parts of purified fuel)

No.	Compound mixed with purified fuel	Parts of sulfur left in ash residue from combustion of 100 parts of mixture at 820° C.	Parts of sulfur left in ash residue from combustion of 100 parts of mixture at 1,000° C.
1	$MgSO_4$.............	0.25	0.01
2	MgO................	.29	.01
3	$MgCO_3$.............	.19	.01
4	Mg_2SiO_4...........	.07	.01
5	$CaSO_4$, $2H_2O$....... (For comparison)	1.51	[2] 1.33

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[1] For coke, according to table 1B.

[2] With 1.64 percent added sulfur, the loss at 1,000° C. amounts to about 19 percent in comparison with about 11 percent at 900° C. Difference not particularly great.

Donath

Donath (18) experimented with two coals and a coke mixed with lime, burning the mixtures until no combustible matter was visible, and analyzing the residue for sulfur content. His results were as tabulated:

Type of fuel	Lime added, percent	Sulfur remaining in the residue, expressed in percent of sulfur of fuel
Coal with 1.24 percent sulfur	None	17
Do....................	1	68
Do....................	2	69
Coal with 9.01 percent sulfur	None	7
Do....................	1	13
Do....................	3	19
Do....................	6	30
Do....................	10	29
Coke with 1.3 percent sulfur.	None	11
Do....................	1	25
Do....................	3	42

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